LATE CENOZOIC BASALTS, UPLANDS PROVINCE, N.E. VICTORIA: IN RELATION TO THE NEWER VOLCANICS BASALTS OF WESTERN VICTORIA

Frederick L. Sutherland[1], Ian T. Graham[1] & Horst Zwingmann[2]

[1]Geodiversity Research Centre, The Australian Museum, 6 College St, Sydney, NSW 2010
[2]CSIRO Petroleum, PO Box 1130, Bentley, WA 6102

The Uplands Province of NE Victoria consists of two petrographically and geochemically similar basalt types of two distinct ages (2.3 and 3.6 Ma) that erupted as flows during peak Pliocene volcanic activity in the Newer Volcanics Province of western Victoria (2-4 Ma). The lavas are enriched transitional olivine basalts whose trace element chemistry has characteristics of both the Plains and Cones series basalts of the Newer Volcanics Province. Detailed isotopic studies (Sr, Nd, Pb) on the older basalt suggests that mixed asthenospheric melt-crustal interactions occurred during basalt genesis. The basalts have been moderately dissected since their initial eruption at 3.6 Ma, with an average downcutting rate of 5 mm/yr.

Key words: Uplands Province, Newer Volcanics Province, olivine basalts, isotopes, petrogenesis, Pliocene, erosion rate.

THE UPLANDS Province of north-eastern Victoria, (previously the Morass Creek volcanics of Hills, 1938) was first correlated with the Newer Volcanics Series by Howitt (1879). These volcanics were mapped as such on the Geological Survey of Victoria maps up until 1902. After this, all the volcanic occurrences east of Melbourne were assigned to the Older Volcanics Series (Hills 1938), although Easton (1937) still related them to the Newer Volcanics Series. On the Tallangatta Geological Survey of Victoria map (Bolger and King 1976), they were named as the Morass Creek Basalt Unit and given a Late Pliocene age, completely separate from the Older Volcanic Series.

The origin of enriched geochemical signatures observed in many continental intraplate basalts such as the Late Cenozoic basalts of Victoria is an ongoing debate that follows two main schools of thought:

1) these signatures come from a subcontinental lithospheric mantle source (e.g. Allegre et al. 1982; McDonough et al. 1985; Turner and Hawkesworth 1995; Stewart and Rogers 1996; Price et al. 1997).

2) these signatures reflect crustal contamination of asthenospheric mantle or plume-derived melts en route to the surface (e.g. Hawkesworth and Vollmer 1979; Carlson et al. 1981; Chesley and Ruiz 1998).

Here, we present new geochemical and isotopic data for the Uplands Province basalts and compare them with the Newer Volcanics Province of western-central Victoria. We comment on the enriched geochemical signatures within these Late Cenozoic basaltic provinces, in relation to the two cited models, and their relationships to mid ocean ridge basalts (MORB) and oceanic island basalts (OIB) sources. Two MORB-types are represented in the underlying eastern Australian asthenosphere, Indian-type MORB (I-MORB) and Pacific-type MORB (P-MORB).

GEOLOGICAL SETTING

The Uplands Province (Wellman 1974) lies in the eastern highlands 9 km north of Benambra. Several basaltic flows extend for at least 20 km along the valley floors of Deep Creek, Morass Creek and Mitta Mitta River (Fig. 1). Hills (1938) described the physiographic settings, recognised several superimposed flows along cliff sections and believed a hill rising above Frasers Tableland marked an eruptive centre. According to Easton (1937), the basalts flowed along the valleys of the tributary streams and the valley of Gibbo River where they dammed the river and initiated a lake. Wellman (1974) equated these basaltic rocks with the Newer Volcanics Province of Western Victoria on the basis of their young age, physiographic settings, vesicular nature of the flows, and the common occurrence of 'iddingsitised' olivine. He estimated the original volume of basalts to be
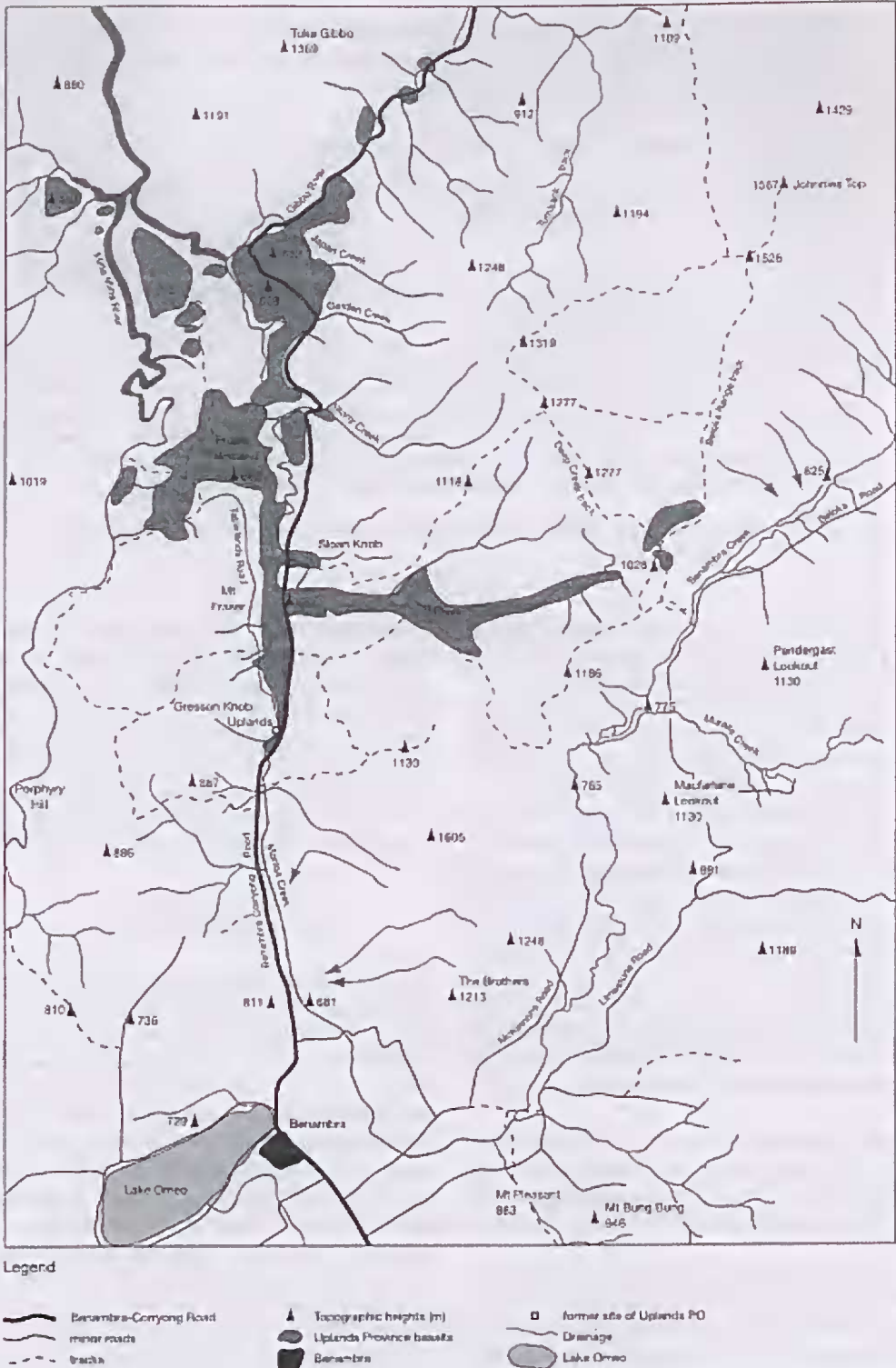
Fig. 1.   Location and extent of the Uplands Volcanic Province (Geology adapted from Bolger and King, 1976). Map area extends from 147° 37' E to 147° 52' E (west to east) and 36° 42' S to 37° 00' S (north to south).
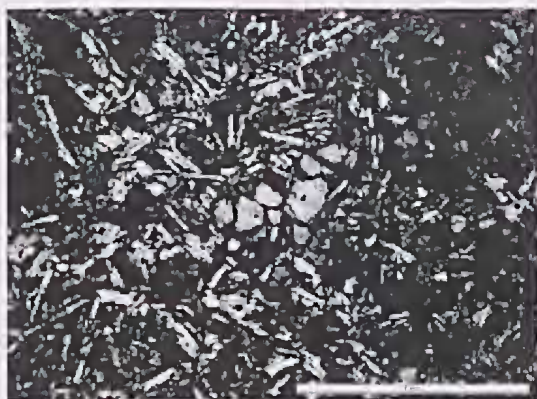
Fig. 2. Photomicrograph of basalt from Stony Creek (field of view 4 mm across; crossed polars).

some 2 km³, based on their present thickness and extent.

Most of the flows infill relative topographic lows in the area. In some cases, the basalts directly overlie the foliated Ordovician metasedimentary sequence (e.g. the hill above Deep Creek crossing at 620m asl; 36° 49.8'S 147° 42.6'E). Elsewhere, they overlie weathered Lower Triassic alkali granitic rocks of the Mount Leinster Complex (e.g. Stony Creek at 620m asl; 36° 48.0'S 147° 42.8'E). Overall, individual flows are generally only a few metres thick, but where Morass Creek has deeply incised through the area, flows of up to at least 50m thickness are seen (e.g. near 36° 49.8'S 147° 42.6'E), suggesting infilling of a steep palaeovalley.

Two distinct flows are discernible between 920 and 960m asl along the forestry track off Beloka Road, about 3 km north-west of Pendergast Lookout (near 36° 49.9'S 147° 47.5'E). Here, a fine-grained relatively massive micro-vesicular olivine basalt flow with a weathered vesicular top and base is sharply overlain by a highly scoriaceous fine-grained olivine basalt with a highly vesicular base. The overlying basalt occupies a channel cut into the lower basalt and the adjacent metasediments suggesting a period of lateral drainage incision between the two phases of eruption. The basalts reach their highest elevation here, suggesting an eruptive source from the east, from where flows descended into Deep Creek valley to below 680m asl. Further sources may lie in the centre of the field near Fraser Tableland, as vertical dyke-like basalt bodies (2m wide and 3m high) intrude the main basalt tongue at Stony Creek (36° 48.0'S 147° 42.8'E) and may represent feeders for higher flows. The basalts reach their lowest topographic levels to the north-west, where they descend

to 500m asl near the junction of the Gibbo and Mitta Mitta Rivers.

PETROGRAPHY

All of the basalts studied are petrographically very similar, though two textural types are apparent; a fine-grained relatively massive micro-vesicular olivine basalt and a fine-grained highly scoriaceous olivine basalt. Under the microscope, they exhibit micro-porphyritic to glomeroporphyritic intergranular textures, generally defined by moderately common phenocrysts and phenocrystic aggregates of olivine and rarer titanian augite, set in a groundmass of non-aligned plagioclase laths, along with intergranular olivine and titanian augite (Fig. 2). Accessory phases include abundant apatite (generally prismatic 'needle-like' grains), platy ilmenite and equant magnetite. Minor phases in some flows include late segregations of feldspar and devitrified glassy patches.

Basalt phases

Olivine phenocrysts (0.25 to 3mm, av. 0.5mm) are generally ovoid subprismatic grains with sharp boundaries against the groundmass phases. They range from weakly fractured unaltered to highly fractured, marginally altered grains. Many contain tiny subhedral equant opaque spinel inclusions. Skeletal, highly embayed xenocrystic grains are rare. The phenocrystic aggregates range up to 2mm across and contain grains with embayed boundaries.

The phenocrystic and groundmass titanian augite grains are all weakly pleochroic (paler to darker pink-brown or colourless to pale pink), anhedral to subhedral, equant to prismatic grains (<<0.1 to 2mm). Most occur in interlocking intergranular aggregates. Some show compositional zoning (with dark pink-brown rims and colourless cores) and many have cuspate-lobate boundaries with groundmass phases, particularly plagioclase. Some grains have narrow replacement rims of chlorite/goethite. Within moderately fractured grains, there is also fracture replacement by fine-grained chlorite/goethite.

Plagioclase (<0.1 to 1.3mm, av. 0.5mm) forms subhedral laths with embayed boundaries with other groundmass phases. Well-developed multiple twin lamellae are common and some crystals show moderate to well-developed core to rim zoning from

more calcic to sodic compositions. Alkali feldspar occurs as a late interstitial phase, commonly as cuspate-lobate forms. Most are untwinned, although some grains have well-developed simple and polysynthetic twin lamellae, indicative of anorthoclase. Chalcedonic quartz/chlorite pseudomorphs after former glass form cuspate-lobate patches in some basalts.

Vesicles/Amygdales

Vesicles and amygdales range in size from <<0.1 to 35mm, and are mostly spherical to ellipsoidal, though cuspate-lobate forms appear within some basalts. They range from empty (vesicles) to a range of infillings (amygdales) including:

1. Zoned narrow walls of chlorite/goethite with central infillings of carbonates.
2. Complete infillings of carbonates.
3. Complete infillings of prismatic zeolites.

Alteration within the basalts varies from very minor (goethite along fractures) to pervasive (partial replacement of ferromagnesian phases and interstitial mixtures of chlorite and goethite). Secondary assemblages vary and include:

1. Fracture and rim-related replacement of olivine by fine-grained mixtures of chlorite/goethite (iddingsite).
2. Goethite replacement of opaques and ferromagnesian minerals.
3. Chlorite rims around titanian augite.
4. Interstitial patches of chlorite.
5. Carbonate/chlorite replacement of olivine.
6. Fine-grained mixtures of clays and quartz replacing alkali feldspar.

7. Interstitial patches of zeolites.

ANALYTICAL METHODS

Potassium-argon analysis

The K-Ar isotopic age determination was made on basalt chips (< 10mm across), crushed with a shatter box (Siebtechnik ring grinder with chrome steel barrel) into a <500 µm fraction. Potassium concentration was determined by atomic absorption (Varian AA 20) using Cs at a concentration of 1000 ppm for ionisation suppression. A 100 - 200 mg of sample aliquot was dissolved with HF and HNO_3 (Heinrichs and Herrmann, 1990), and then diluted to 0.3 to 1.5 ppm K for the atomic absorption analysis. Ar isotopic determination followed a similar procedure to Bonhomme et al. (1975). The sample was pre-heated under vacuum at 80° C to reduce atmospheric Ar adsorbed onto the mineral surfaces. Argon was extracted from the separated mineral fractions by fusing the sample within a vacuum line serviced by an on-line ^{38}Ar spike pipette. The isotopic composition of the spiked Ar was measured using a high sensitivity on-line VG3600 mass spectrometer. The ^{38}Ar spike was calibrated against the international standard biotite GA1550 (McDougall and Roksandic 1974). After fusion of the sample in a low blank Heine resistance furnace, the released gases were purified with a Cu_2O getter for the first step and two TiO_2 getters for the second step. Blanks for the extraction line and mass spectrometer were systematically determined and the mass discrimination factor was determined periodically by airshots. International standards were measured for calibration purposes. The uncertainty for the argon analysis is below 1 %. The K-Ar age was calculated using ^{40}K concentration and decay constants recommended by Steiger

Location	Rocktype	K (%)	^{40}Ar (%)	Age (Ma)
[1]Stony Creek	Massive basalt	1.33	8.62	$3.59 \pm 0.44 (\pm 2 \sigma)$
[2]2km N Uplands PO	Scoriaceous basalt	1.57	59.2	$2.32 \pm 0.06 (\pm 2 \sigma)$
[2]3km N Uplands PO	Scoriaceous basalt	1.48	59.3	$2.33 \pm 0.06 (\pm 2 \sigma)$

([1] this study; [2] recalculated ages of Wellman, 1974)

Table 1. K-Ar wholerock geochronology for the Uplands Province.

and Jager (1977). The age uncertainty takes into account the errors during sample weighing, $^{38}Ar/^{36}Ar$ and $^{40}Ar/^{38}Ar$ measurements and K analysis. The sample analysed yielded a low radiogenic ^{40}Ar concentration of 8.62%, which produced the relatively high uncertainty.

Major and minor elements

The major, minor and selected trace elements were analysed by Maggi Loubser at the XRF and XRD Facility, University of Pretoria, Pretoria, South Africa, using X-ray fluorescence (XRF). Initially, samples were ground to <75 µm in a mild steel milling vessel, roasted at 1000°C to determine Loss On Igni-

Sample	DR 16926	DR 16930	DR 16899
Locality	Stony Creek	Gibbo Park	Uplands PO
Latitude	36° 48.0' S	36° 45.8' S	36° 50.0' S
Longitude	147° 42.8' E	147° 41.8' E	147° 42.3' E
Elevation	640m	520m	640m
Rock type	Massive basalt	Vesicular basalt	Scoriaceous basalt
SiO_2	48.52	50.09	49.72
TiO_2	1.92	1.95	1.96
Al_2O_3	14.48	15.59	14.93
Fe_2O_3	2.31	2.43	2.33
FeO	8.33	8.75	8.40
MnO	0.15	0.16	0.15
MgO	7.76	7.62	7.39
CaO	8.45	8.34	8.18
Na_2O	2.96	3.23	3.55
K_2O	1.62	1.65	1.59
P_2O_5	0.53	0.59	0.54
LOI	1.24	0.90	0.19
Total	98.27	101.30	98.93

CIPW Norm, Anhydrous, with $Fe_2O_3/(FeO+Fe_2O_3) \sim 0.2$.

Or	9.86	9.71	9.51
Ab	25.80	27.21	30.41
An	22.09	23.07	20.36
Mt	3.46	3.51	3.43
Il	3.76	3.69	3.77
Ap	1.29	1.39	1.29
Di	14.23	11.62	13.94
Hy	8.13	7.74	3.37
Ol	11.37	12.05	13.91
Cm	0.05	0.04	0.04
D.I	35.67	36.92	39.92
An%	46.12	45.88	40.10
Mg No.	62.41	60.81	61.06

Analyst: M.Loubser, Department of Geology, University of Pretoria, South Africa.
Note that analytical totals fall outside normal ranges, due to uncertainties in the ignition loss determinations. The other oxide values fall within accepted ranges for the international rock standards used.

Table 2.   XRF major and trace element analyses and CIPW norms.

tion (LOI), and, after adding 1 gram of sample to 6 grams of $Li_2B_4O_7$, fused into a glass bead. XRF analyses were then executed on the fused glass bead using an ARL 9400XP+ spectrometer. For selected trace element analyses, another aliquot of the sample was pressed into a powder briquette.

Trace and rare earth elements (REE)

These were analysed by Dr Andreas Spath at the Geology Department, University of Cape Town, Rondebosch, South Africa, using inductively coupled plasma mass spectrometry (ICP-MS). This involved the dissolution of 50 mg of each sample with a standard acid digestion procedure using ultra-clean HF and HNO_3. Standards were made-up from artificial multi-element standard solutions. The samples were analysed on a Perkin Elmer Seiex Elan 6000 ICP-MS. The instrument operating conditions were typically:

Sample	DR 16926	DR 16930	DR 16899
Rocktype	Massive basalt	Vesicular basalt	Scoriaceous basalt
Sc	16.9	17	17.4
V	169	163	172
Cr	223	196	223
Co	56.7	52.3	64.9
Ni	147	137	147
Cu	53.9	56.8	54.4
Rb	30.5	22.5	24
Sr	697	592	643
Y	17.2	17.7	17.7
Zr	171	177	174
Nb	40.9	42.4	41.9
Cs	1.18	0.34	0.25
Ba	315	275	328
La	24	25.9	24.7
Ce	46.2	49.4	47.4
Pr	5.48	5.89	5.6
Nd	23.1	24.5	23.6
Sm	4.77	5.03	4.95
Eu	1.68	1.75	1.72
Gd	4.89	5.09	4.99
Tb	0.68	0.71	0.69
Dy	3.74	3.88	3.87
Ho	0.68	0.70	0.68
Er	1.69	1.72	1.73
Tm	0.22	0.22	0.22
Yb	1.27	1.33	1.30
Lu	0.18	0.18	0.18
Hf	3.62	3.75	3.69
Ta	3.74	3.85	3.87
Pb	2.67	2.78	2.66
Th	3.00	3.07	3.08
U	0.95	1.02	0.95
Ga*	22	24	22

Analyst: A.Spath, Department of Geology, University of Cape Town, South Africa.
(* determined by XRF; Analyst: M.Loubscr, Department of Geology, University of Pretoria, South Africa)

Table 3.   ICP-MS trace and rare earth element analyses.

Nebuliser gas flow of 0.81 L/min; Main gas flow of approx. 15 L/min; Auxilliary gas flow of approx. 0.75 L/min; Autolens voltages were $^9Be = 8.6V$, $^{59}Co = 9.2V$, and $^{115}In = 9.8V$; the ICP RF forward power was 1100W. The instrument operating conditions were optimised to minimise the formation of doubly-charged ion ($Ba^{2+}/Ba^+ < 0.03$) and oxides ($CeO/Ce < 0.03$). The instrument sensitivity for ^{103}Rh was approx. 25 000 cps/ppb. Three replicates of each sample were analysed with 20 sweeps per replicate. The dwell times were 35-50 ms per mass peak and the analytical time for each sample was 1:41.58 min. Internal standardisation was achieved using ^{103}Rh, ^{115}In, ^{187}Re and ^{209}Bi. Interference corrections were made for isobaric interferences and for the more severe doubly-charged ion and oxide interferences (particularly on the REE).

Strontium, neodymium and lead isotopes

The techniques for chemical separation and measurement of these isotopes follow procedures described by Zhang et al. (2001). Sr and Nd isotopes were determined by Karen Blacklock from CSIRO Petroleum, North Ryde, Sydney, NSW. The $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ ratios were measured on a VG Sector 354 mass spectrometer with multiple collectors on its fully automatic mode and normalised to $^{86}Sr/^{88}Sr = 0.1194$ and $^{146}Nd/^{144}Nd = 0.7219$ respectively. Replicate analyses of NBS SRM 987 gave $^{87}Sr/^{86}Sr = 0.710287 \pm 0.000012$ (external precision at 2ó) and the O'Nions standard gave $^{143}Nd/^{144}Nd = 0.511116 \pm 0.000014$ (external precision at 2ó).

Lead isotopes were determined by Barbara Gardner and Geoff Denton from CSIRO Exploration and Mining, North Ryde, Sydney, NSW. Lead isotope compositions were analysed on a thermal ionisation mass spectrometer (TIMS VG-1SOMASS 54E) run in fully automated mode after dissolution of samples using acid digestion techniques. The precision on the isotopic ratios based on > 2000 analyses of the international standard SRM 981 and replicate analyses of natural samples is ± 0.05% (2ó) for the $^{208}Pb/^{206}Pb$ and $^{207}Pb/^{206}Pb$ ratios and ± 0.1% (2ó) for the $^{206}Pb/^{204}Pb$. Data were normalised to international standards NBS SRM 981, by applying a correction factor of +0.08% amu to allow for comparisons between laboratories.

RESULTS

K-Ar dating

Both new (this study) and old (Wellman, 1974) K-Ar dating for the Uplands Province (Table 1) shows that the basalts are Middle to Late Pliocene in age, ranging from 2.32 Ma for scoriaceous basalt at Uplands in the south (Wellman 1974), to 3.59 Ma for massive basalt at Stony Creek near the centre of the province. This age difference of 1.27 Ma suggests at least two episodes of eruption (see above), although further flows between the dated flows may be present.

Major elements

The compositions and norms of three basalts (Table 2) are very uniform with a restricted range, i.e. SiO_2 (48.5-50.1), TiO_2 (1.9-2.0), Al_2O_3 (14.5-15.6), FeO

$^{87}Sr/^{86}Sr$	(2 σ)	$^{143}Nd/^{144}Nd$	(2 σ)	εNd
0.704905	0.0013	0.512805	0.0017	3.400

(Analyst: K. Blacklock, CSIRO Petroleum, Sydney, NSW)

$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$	Pb (ppm)
18.306	15.544	38.257	1.35

(Analyst: B. Gardner, CSIRO Exploration and Mining, Sydney, NSW)

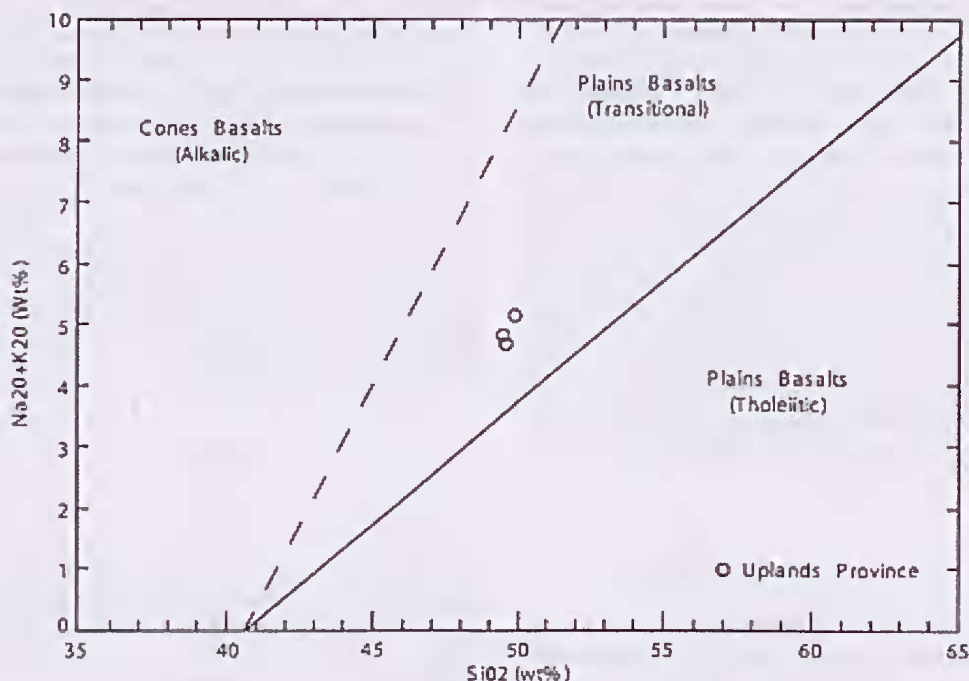Table 4.   Strontium, neodymium and lead radiogenic isotope data for Stoney Creek basalt (DR 16926).

Fig. 3. Total alkalis vs silica diagram (after Vogel and Keays 1997).

(8.3-8.8), MgO (7.4-7.8), CaO (8.2-8.5), Na_2O (3.0-3.6), K_2O (1.6-1.7) and P_2O_5 (0.5-0.6). In normative terms (using a calculated $FeO/(FeO+Fe_2O_3)$ of 0.2), they contain diopside (11.6-14.2), hypersthene (3.4-8.1) and olivine (11.4-13.9), and can be classified as transitional olivine basalts. The Mg values (60.8 - 62.4), differentiation index (35.7 - 39.9) and anorthite% (40.1 - 46.1) suggest they are moderately evolved basalts. On the TAS diagram of Le Maitre (1989), the basalts of the Uplands Province plot as either basalts or trachyandesites. They are essentially hawaiites transitional to olivine tholeiites.

Minor and trace elements

In terms of trace elements (ppm, Table 3), the Uplands Province basalts show little variation in chemistry with moderately high Cu (54-57); moderate V (163-172), Cr (196-223), Ni (137-147), Rb (23-31), Sr (592-697), Y (17-18), Zr (171-177), Nb (41-42), Ba (275-328); and low Hf (3.6-3.8), Ta (3.7-3.9), Pb (2.7-2.8), Th (3.0-3.1) and U (0.9-1.0).

Vogel and Keays (1997) distinguished three main compositional suites amongst the Newer Volcanics Province of Western Victoria using the total alkali vs silica diagram (of Macdonald and Katsura 1964) termed these Cones Basalts (alkalic), Plains Basalts (transitional) and Plains Basalts (tholeiitic). On this diagram (Fig. 3), the Uplands basalts clearly fall into their Plains Basalts (transitional) suite. Furthermore, using the fields for their three basalt suites on trace element plots, the Uplands basalts plot with their transitional basalts on both the Zr vs Nb (Fig. 4) and Sr vs Nb (Fig. 5) diagrams. On the Gd/Yb vs La/Sm diagrams, the Uplands plots lie outside the transitional field due to higher La/Sm ratios, but are much closer to this field than for the other basalt fields. However, on the Nb/Zr vs Nb/Y diagram, they plot just within the field for alkalic basalts, although still close to the transitional field. Thus, in geochemistry, the Uplands basalts resemble the transitional Plains Series basalts of the Newer Volcanics Province, although with minor differences.

On the extended multi-element primitive-mantle normalised diagram (Fig. 6), the basalts exhibit distinct positive anomalies for Nb and Ti, and negative anomalies for Rb, Cs, Pb, Th, Ce, Sc, V, Ni and Cr. This again attests to their transitional nature, suggesting a moderate degree of fractionation.
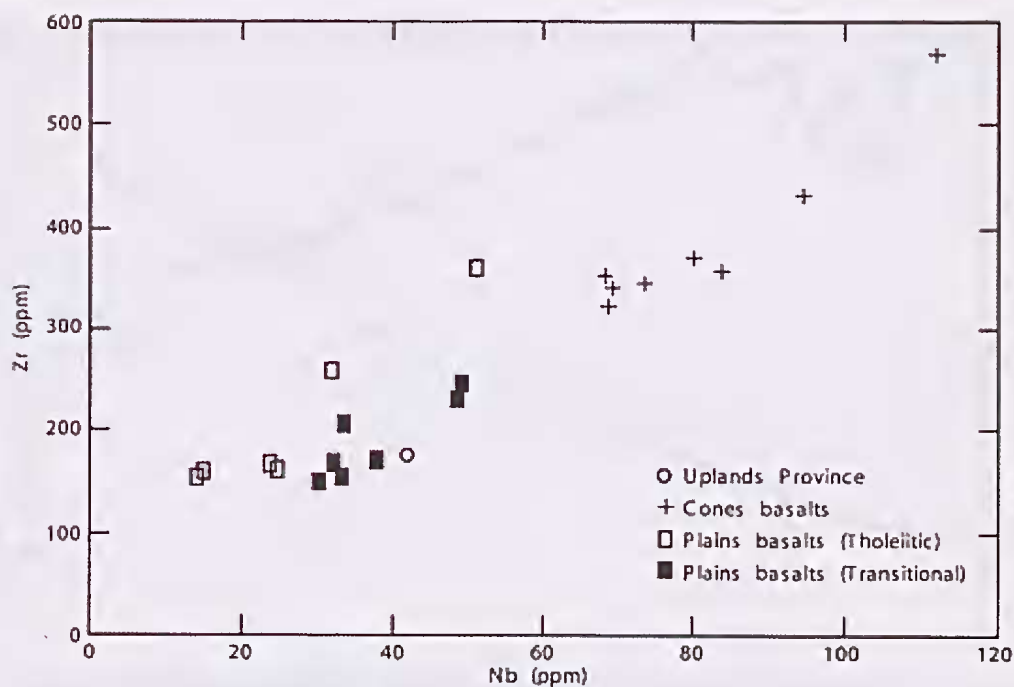
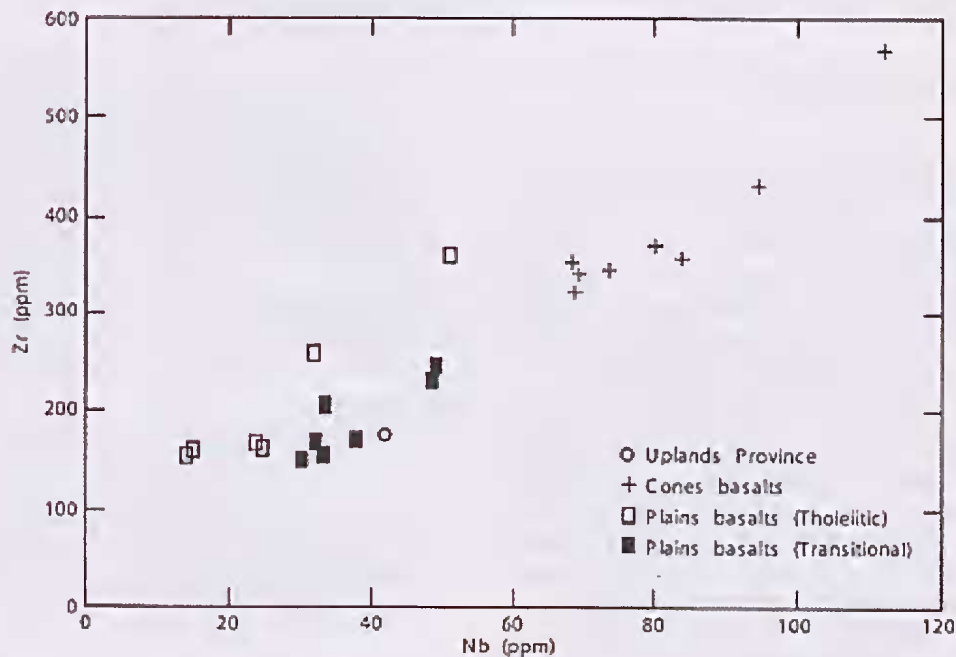Fig. 4. Zr vs Nb diagram (after Vogel and Keays 1997).

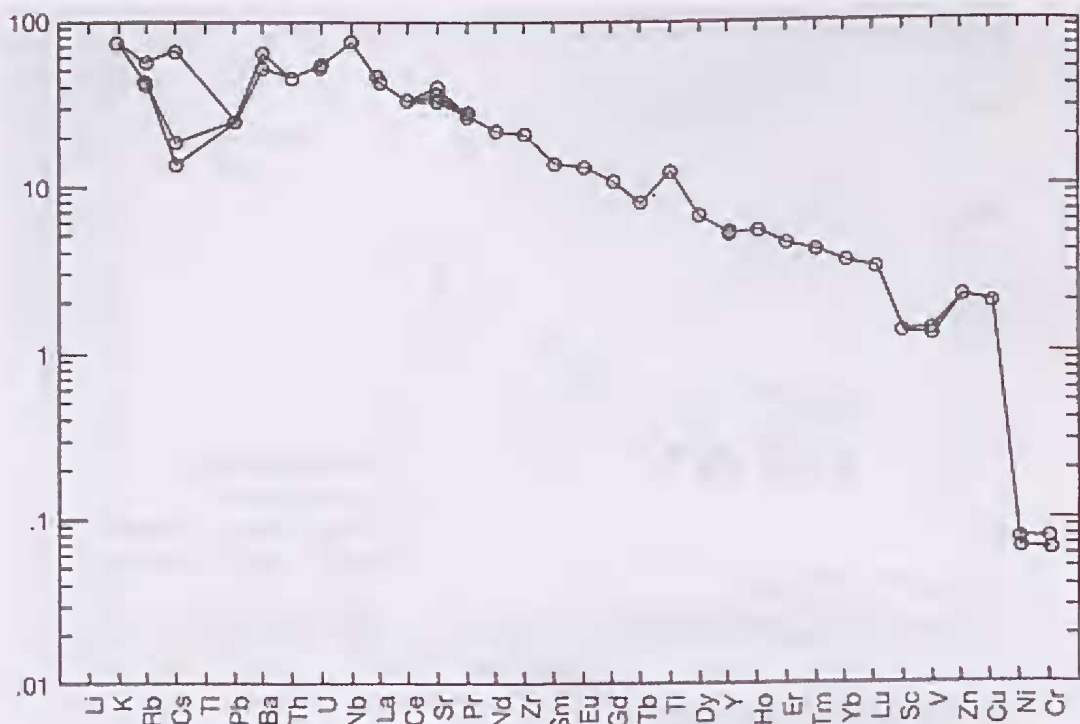Fig. 5. Sr vs Nb diagram (after Vogel and Keays 1997).

Fig. 6. Primitive mantle-normalised (rock / primitive mantle) multi-element diagram (Note: general degree of parallelism and overlapping between the three samples). Normalising values after Taylor and McLennan (1985).

Rare earth elements (REE)

The Uplands basalts have a uniform REE chemistry (Table 3) with moderate light REE (LREE) abundances (e.g. La 24.0-25.9; Ce 46.2-49.4) and low heavy REE (HREE) abundances (e.g. Ho 0.68-0.70; Yb 1.27-1.33). On the primitive mantle-normalised REE diagram (Fig. 7), the Uplands basalts are more enriched in the LREE compared to the HREE, resulting in a moderately steeply-dipping curve. The overall pattern resembles that for transitional basalts of the Western Plains sub-province of the Newer Volcanics (Price et al. 1997), but with slightly lower HREE concentrations. They suggested that the Plains Series basalts match those found in other intraplate basalt provinces (e.g. Thompson et al. 1983; Huang et al. 1997). Overall, the Uplands Province basalts are significantly lower in HREE compared to typical MORB, suggesting that they were probably generated from a source retaining residual garnet (i.e. possibly the lithospheric mantle).

Sr, Nd and Pb isotopes

The Sr, Nd and Pb isotopic analyses are presented in Table 4. Based on leaching experiments and weathering studies from the Newer Volcanics basalts, Price et al. (1991), concluded that the Sr isotopic characteristics were only slightly modified by late-stage groundwater infiltration (see also McDonough et al. 1985; Price et al. 1997). McBride et al. (2001) using osmium isotopic signatures for these basalts also concluded the basalts were not significantly modified by late-stage alteration. Thus, the isotopic signatures observed in the basalts represent unmodified signatures.

A regional discontinuity was defined in the Newer Volcanics Province, on observed strontium isotopic compositions (whether from the Plains Series or Cones Series) along a N-S line which passes through Mortlake (the 'Mortlake Discontinuity'; Price et al. 1988, 1997; Nicholls et al. 1993). East of this line the basalts generally have a more radiogenic Sr iso-

Fig. 8. εNd vs $^{87}Sr/^{86}Sr$ diagram. Lithospheric fields Victorian plains and cones basalt plots and Tasmanian basalt plots are adapted from McDonough et al. (1985) and McBride et al. (2001).
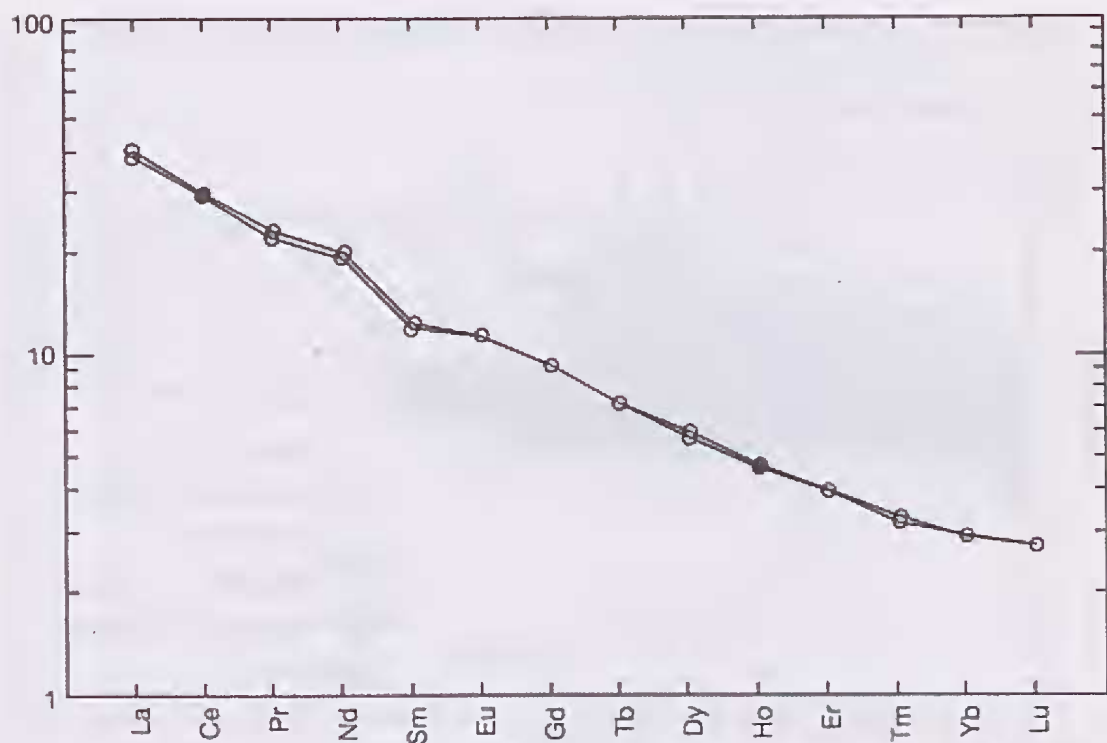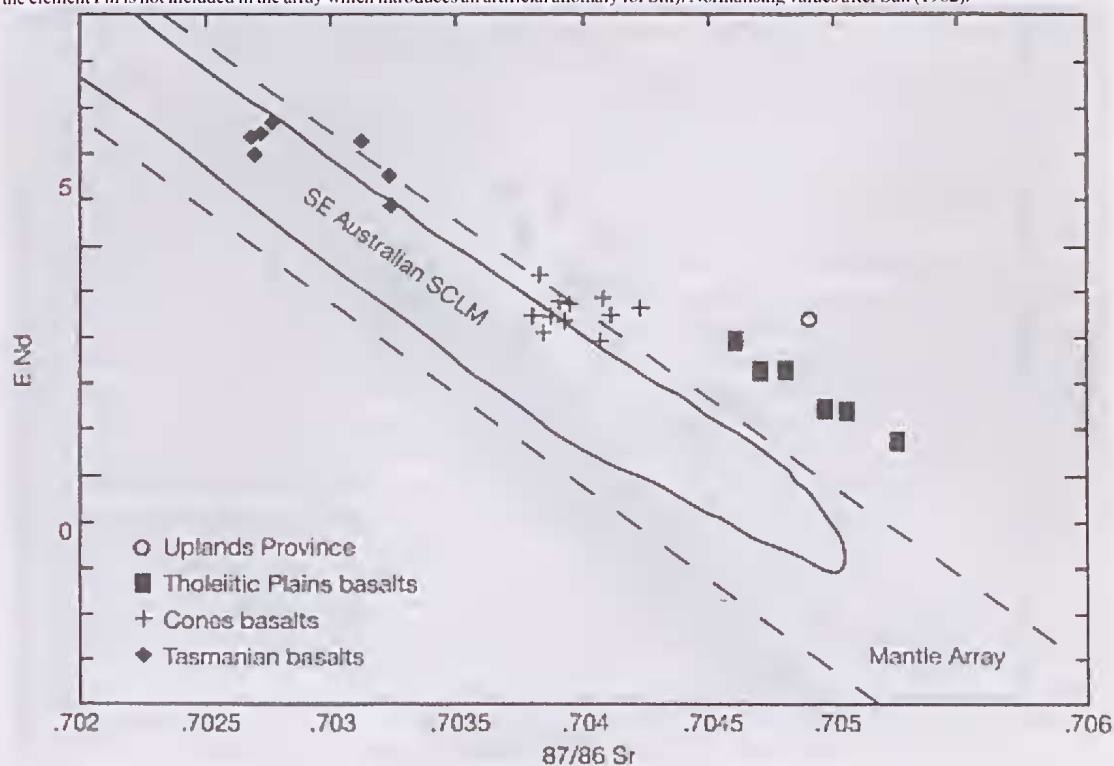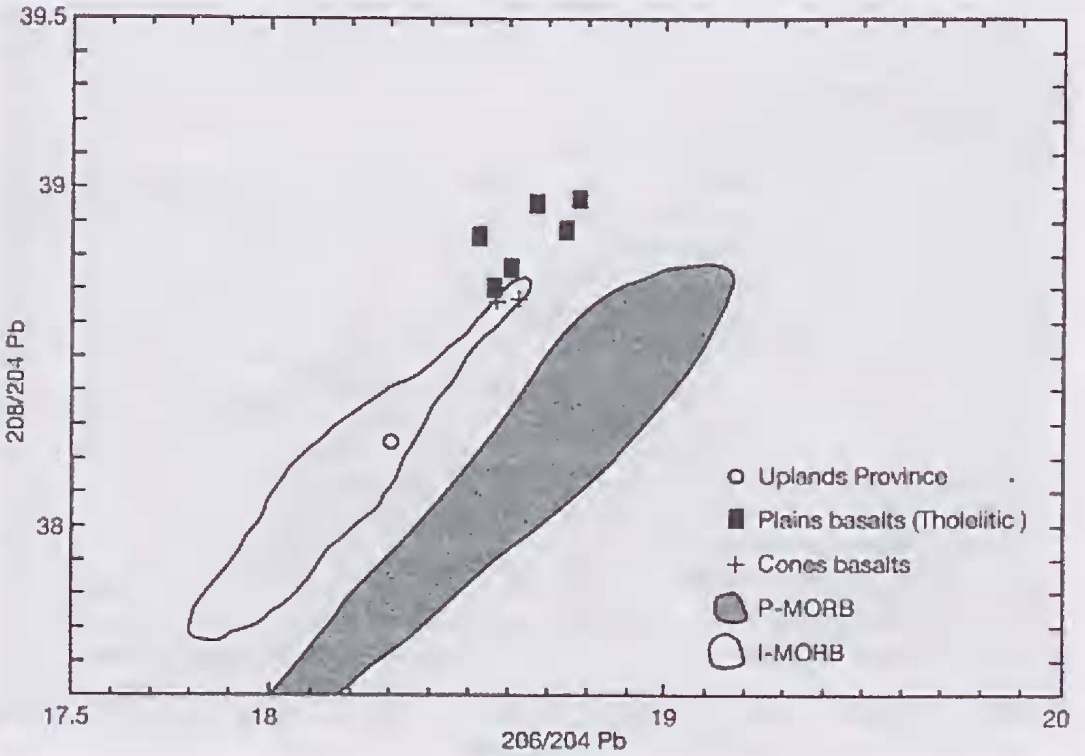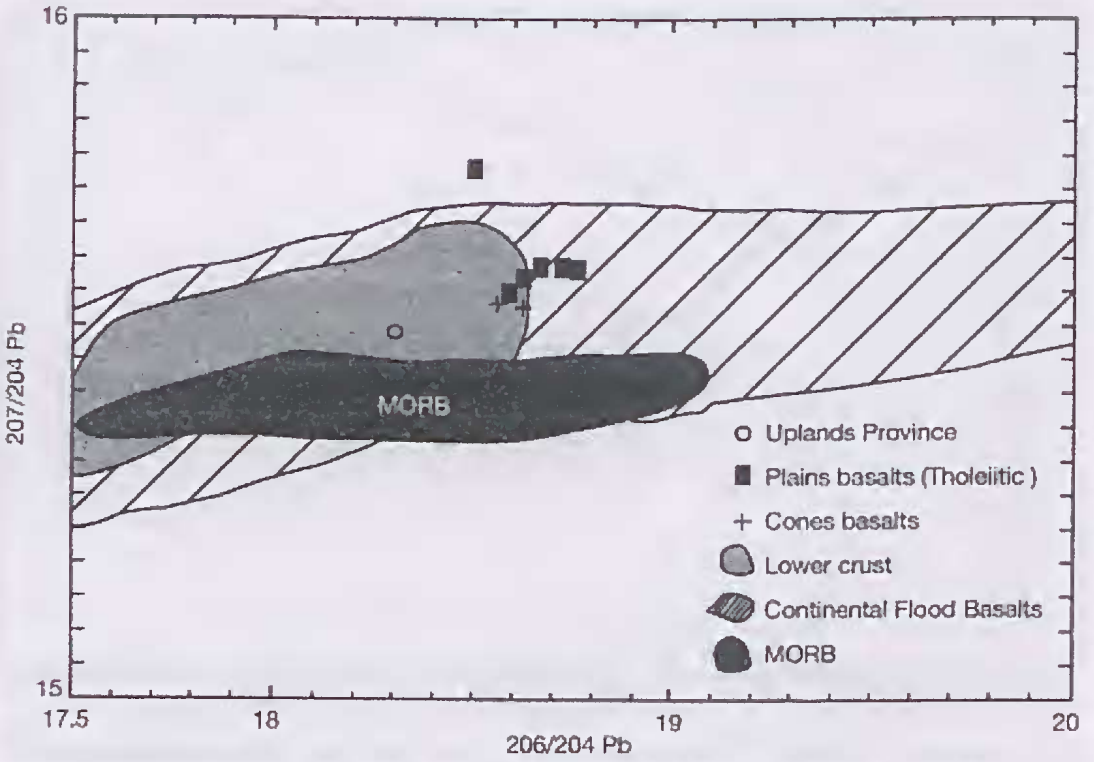
Fig. 7. Primitive mantle-normalised (rock / primitive mantle) rare earth diagram (Note: parallelism and overlapping between the three samples; the element Pm is not included in the array which introduces an artificial anomaly for Sm). Normalising values after Sun (1982).
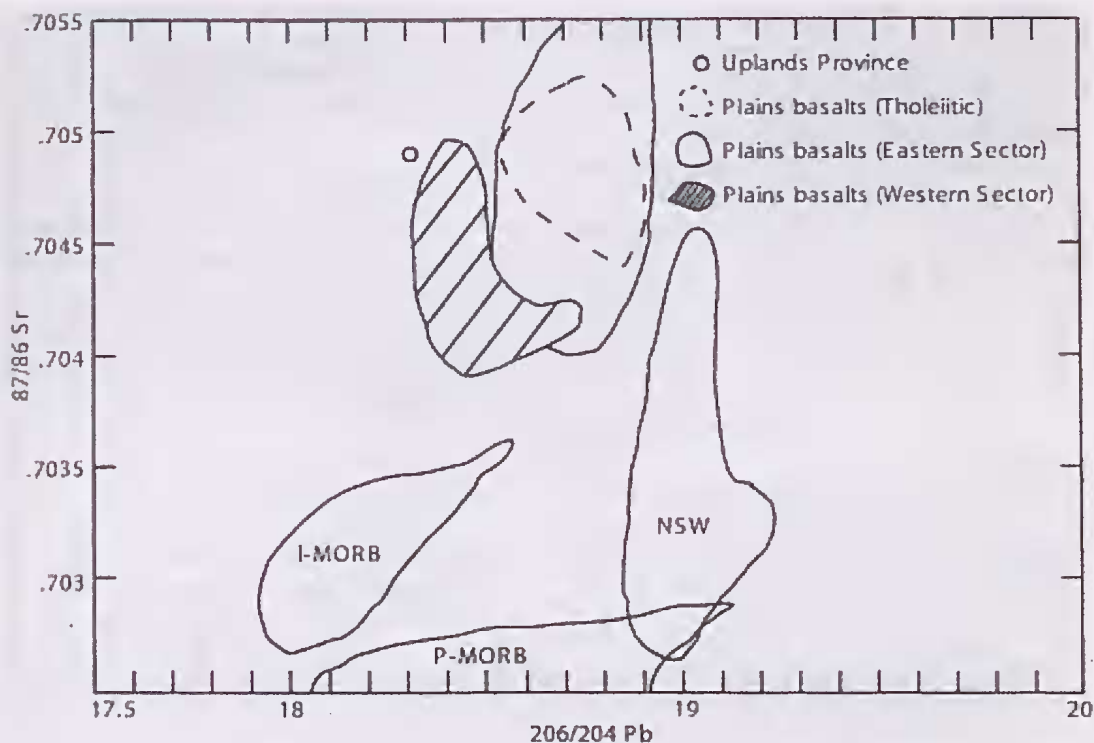
Fig. 10. $^{87}Sr/^{86}Sr$ vs $^{206}Pb/^{204}Pb$ diagram. MORB and NSW basalt fields from Zhang et al. (2001). Plains basalt fields adapted from McDonough et al. (1985) and McBride et al. (2001).

topic signature than those to the west which also includes the Uplands basalt.

On the ϵNd vs $^{87}Sr/^{86}Sr$ diagram (Fig. 8), the Uplands basalt distinctly plots above the mantle array, and just above the field for the tholeiitic Plains Series basalts of the Newer Volcanics Province.

The $^{206}Pb/^{204}Pb$ value for the Uplands basalt at 18.306, lies just below the values for the Newer Volcanics Province. In terms of Pb isotopic characteristics, all of the Newer Volcanics Province basalts analysed fall well to the right of the geochron (Faure, 1986) suggesting that their sources had experienced a long-term history of elevated U/Pb ratios (McBride et al. 2001). Both the Plains Series olivine tholeiites and Cones Series nepheline hawaiites analysed by McBride et al. (2001) have $^{206}Pb/^{204}Pb$ values ranging from 18.57 to 18.84, within the range for the Newer Volcanics Province (18.4 to 18.9; Price et al. 1997; McBride et al. 2001), and those observed for many ocean-island basalts and continental flood basalt provinces (e.g. Zindler and Hart 1986; Carlson 1991).

On the $^{208}Pb/^{204}Pb$ vs $^{206}Pb/^{204}Pb$ diagram (Fig. 9a), the Uplands basalt plots well away from the Newer Volcanics Province field but well within the Indian Ocean MORB (I-MORB) field and the lower crust. This also applies on the $^{207}Pb/^{204}Pb$ vs $^{206}Pb/^{204}Pb$ diagram (Fig. 9b).

On the $^{87}Sr/^{86}Sr$ vs $^{206}Pb/^{204}Pb$ diagram (Figure 10), the Uplands basalt Province plots away from but close to the tholeiitic Plains Series basalts of the Newer Volcanics Province, being closest to basalts from the western sector. It plots well away from both the New South Wales and Pacific Ocean MORB (P-MORB) fields, but closer to the I-MORB field. On $^{87}Sr/^{86}Sr$ vs $^{208}Pb/^{204}Pb$ values, the Uplands basalt is distinct from the tholeiitic Plains Series basalts of the Newer Volcanics Province.

When ϵNd is plotted against $^{206}Pb/^{204}Pb$, the Uplands basalt plots again shows a similar disposition to the other fields. In $\mathring{a}Nd$ vs $^{208}Pb/^{204}Pb$ values, the

Fig. 9a. $^{208}Pb/^{204}Pb$ vs $^{206}Pb/^{204}Pb$ diagram. MORB fields after Zhang et al. (2001). Plains and cones basalt plots adapted from McDonough et al. (1985) and McBride et al. (2001).

Fig. 9b. $^{207}Pb/^{204}Pb$ vs $^{206}Pb/^{204}Pb$ diagram. Fields and plains and cones basalt plots adapted from McBride et al. (2001).
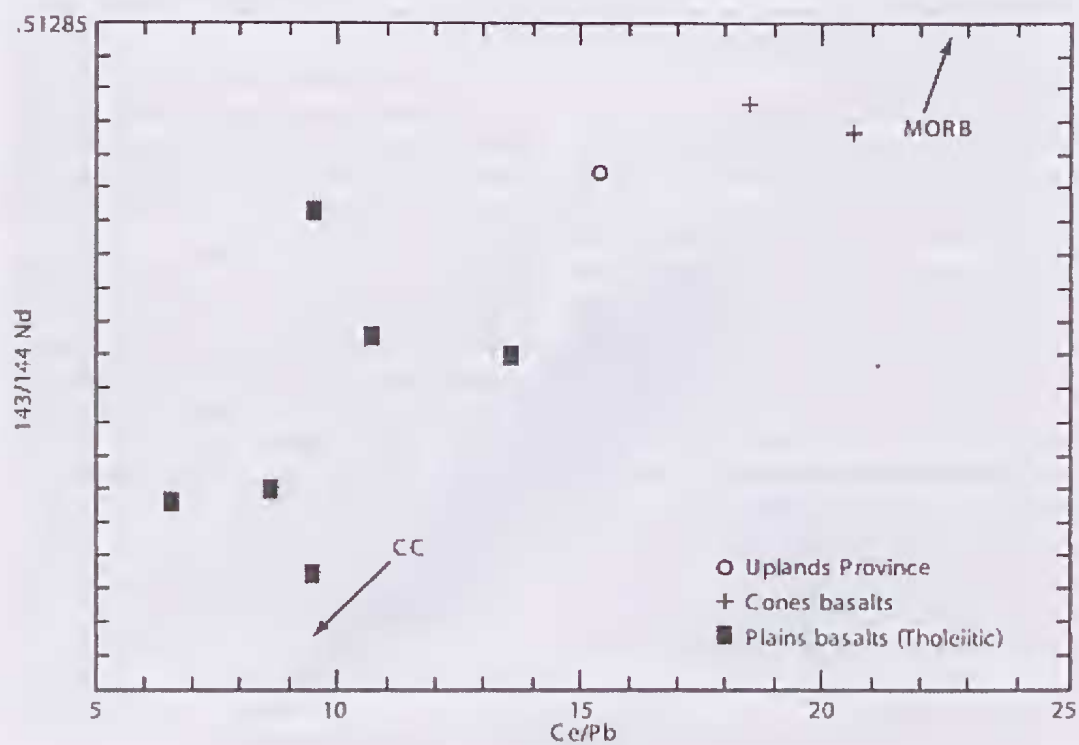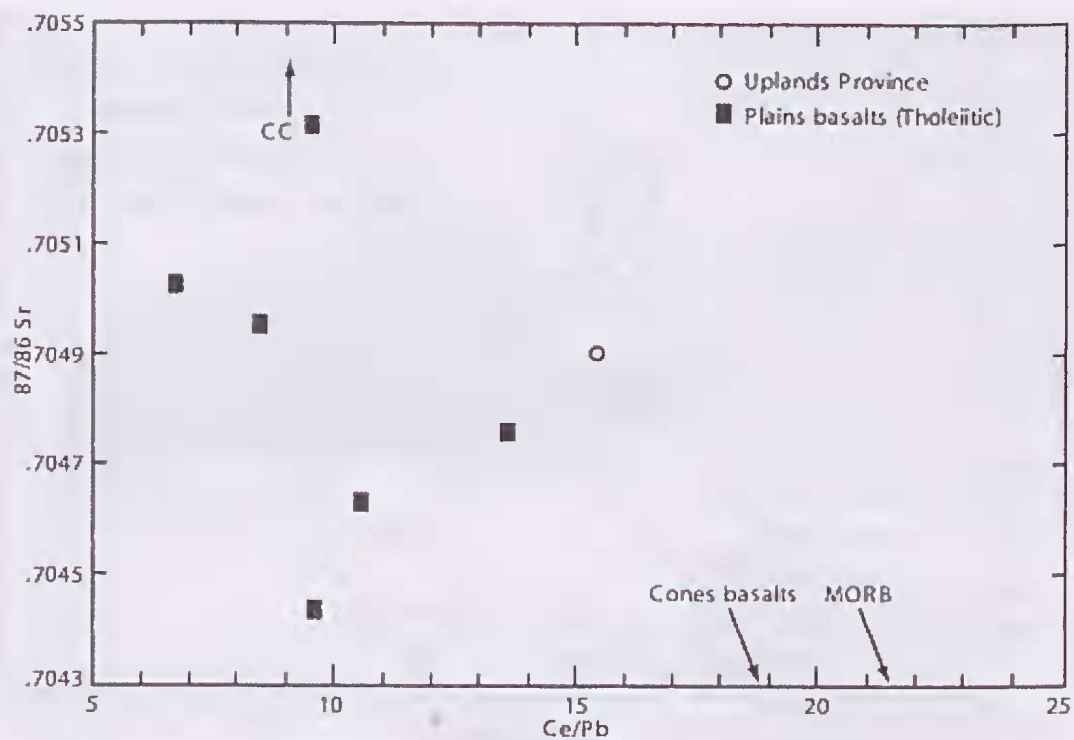
Uplands basalt has lower $^{208}Pb/^{204}Pb$ than the Newer Volcanics Province but lies within the same range of εNd values. For εNd against $^{206}Pb/^{204}Pb$, the Uplands basalt values are closest to the I-MORB related field for North Queensland basalts.

On the $^{87}Sr/^{86}Sr$ vs Ce/Pb diagram (Fig. 11A), the Uplands basalt lies near to the field for the tholeiitic Plains Series basalts, while on the $^{143}Nd/^{144}Nd$ vs Ce/Pb diagram (Fig. 11B), the Uplands basalt plots between the fields for the alkaline Cones Series and tholeiitic Plains Series basalts. On $^{206}Pb/^{204}Pb$ vs Ce/Pb values, the Uplands basalt is distinct from the alkaline Cones Series and tholeiitic Plains Series basalts due to much lower $^{206}Pb/^{204}Pb$ ratios.

DISCUSSION

The Uplands Volcanic Province represents an isolated eastern extension of the Late Cenozoic activity that prevailed in central-western Victoria (Price et al. 2003). This is the first detailed study of the Uplands basalts that allows close comparison with the temporally linked Newer Volcanics Province.

Age implications

The two ages determined for the Uplands Province basalts both lie within those for the Newer Volcanics Province (McDougall et al. 1966; Wellman and McDougall 1974), and correspond with the volumetric peak activity for the Plains Series basalts (spanning 2 to 3 Ma). However, the Uplands Province is at least 280km north-east of the nearest outcrops of the Newer Volcanics Province and forms a separate area of activity.

The further dating extends the age range of the Uplands basalts from 2.3 to 3.6 Ma, probably as two distinct episodes, although intermediary activity is possible. Other scattered activity related to the Uplands event may exist elsewhere in eastern Victoria, as alluvial zircon megacrysts in the Tombullup Province, 120 km to the west, include a group with re-set fission track ages of 3.6 ± 1.8 Ma (Australian Museum, Geotrack Report No 53, 1986) and basalt scoria was mapped some 60 km to the south on Barmouth Spur (Willman et al. 1999).

The presence of two basalts separated in age in the same tributary drainage system entering Mitta Mitta River has implications for downcutting rates in this region. Downcutting time to re-excavate the basalt buried valleys is now 60% longer, decreasing previous estimated erosion rates. About 190m thickness of basalt remains in the Morass Creek Section between Stony Creek and Fraser Tableland, suggesting an overall minimum downcutting rate of some 5 mm/yr since 3.6 Ma. The basalt infills would periodically elevate local drainage base levels for more vigorous downcutting to produce the present gorge-like course of Morass Creek.

Geochemical implications

In major and trace elements, the Uplands basalts are transitional types that resemble the Plains Series basalts of the Newer Volcanics Province, but show some differences. Thus, Ba/Nb ratios for Uplands basalts (6.5-7.8) resemble those of the Cones Series alkali basalts (6.1 − 7.3) rather than the Plains Series olivine tholeiites (11.0 − 17.3) which may incorporate crustal contamination and assimilation (McBride et al. 2001). Price et al. (1997) rejected significant influence of upper continental crust in the Newer Volcanics Province basalts, but left open the influence of variable lower crustal contamination. The possibility of such contamination in the Uplands basalts needs consideration to explain their mixed characteristics relative to the Newer Volcanics basalts.

The Uplands basalts show uniform Ce/Pb (17-18) and Nb/U (42-44). An apparent variation in Pb values for the Stony Creek basalt (Tables 3 and 4) may reflect a difference in analytical methods, the ICP-MS results being more consistent with the other basalt values. These reported ratios guide assessment of continental crust influences (see Hofmann et al. 1986), as they are generally uniform in both MORB and OIB basalts, with Ce/Pb (25 ± 5) and Nb/U (47 ± 10), in comparison to continental crust, with Ce/Pb (4) and Nb/U (10). On this basis, the Uplands basalts suggest some crustal residence and contamination has affected their chemistry. Thus, the Uplands basalts trend away from the Newer Volcanics Cones Series alkaline basalts (Ce/Pb 19 - 21; Nb/U 55) partly towards the crust-like compositions of the Plains Series olivine tholeiites (Ce/Pb 7 − 14; Nb/U

Fig. 11A. $^{87}Sr/^{86}Sr$ vs Ce/Pb diagram. Adapted from McBride et al. (2001).
Fig. 11B. $^{143}Nd/^{144}Nd$ vs Ce/Pb diagram. Adapted from McBride et al. (2001).

22 – 34; McBride et al. 2001).

Isotopic compositions of basalts can also indicate crustal contamination. Thus, while trace element signatures for both Plains Series and Cones Series basalts in the Newer Volcanics are similar to plume-related magmas (McDonough et al. 1985), the Plains Series trend to radiogenic $^{87}Sr/^{86}Sr$ above the mantle array and have high radiogenic Os relative to most OIB values (McBride et al. 2001). The Uplands basalt $^{87}Sr/^{86}Sr$ plots well above the mantle array and also above the field for Plains Series olivine tholeiites. Crustal contamination can be recognised by both high $^{87}Sr/^{86}Sr$ and low εNd values (Ewart et al. 1988; Price et al. 1997) and Uplands basalt with $^{87}Sr/^{86}Sr$ 0.704905 and εNd 3.4 suggests crustal contamination has affected the isotopic systematics en route to the surface. The exact contaminating material is uncertain and may involve Lachlan Orogen components not present at the surface, as suggested by McBride et al. (2001) for the Newer Volcanics Plains Series. Unfortunately, the age of the lower crust in southeastern Australia is still uncertain with estimates ranging from Proterozoic (Cas 1983) to Post-Cambrian (e.g. Gray 1997; Anderson et al. 1998).

On a wider scale, the recent detailed work on the Newer Volcanics Province suggests both Plains and Cones Series basalts are mantle-derived melts (McBride et al. 2001). The Os and Nd isotope characteristics for Plains Series olivine tholeiites suggests variable mixing of two isotopic end-members, continental crust (high χ Os and low ε Nd) and asthenospheric mantle (low χ Os and high ε Nd). Two subgroups were also distinguished in the olivine tholeiites, based on different χ Os, ε Nd and $^{87}Sr/^{86}Sr$ values. However, the Uplands transitional basalts with moderately radiogenic ε Nd and radiogenic $^{87}Sr/^{86}Sr$ differ again from the Plains Series olivine tholeiites adding to the complexity of mantle-crustal melt interactions in the wider Victorian scene.

The Uplands basalts occupy a critical position close to the Indian-Pacific mantle asthenosphere boundary (Sutherland 2003). In terms of Pb isotopes, the Uplands basalt generally plots well within the I-MORB field and distant from the P-MORB field although the $^{207}Pb/^{204}Pb$ vs $^{206}Pb/^{204}Pb$ values lie within the lower crust field and suggest a mixed asthenospheric melt-crustal interaction. The observed fractionation and contamination effects also obscure precise assignment of the Uplands basalt primary magma source. Even so, Pb isotope values tentatively favour an I-MORB connection similar to the west-

ern Newer Volcanics Province, rather than a P-MORB connection that typifies New South Wales basalt fields (see Zhang et al. 1999; Sutherland 2003).

CONCLUSIONS

1. The Uplands Province erupted during peak activity in the Newer Volcanics Province in western Victoria (2-4 Ma).
2. The lavas are evolved olivine basalts with trace element characteristics allied to both the Plains and Cones series basalts of the Newer Volcanics Province.
3. The observed isotope values suggest mixed asthenosphere melt-crustal interactions were involved in basalt genesis.
4. The basalts have been dissected since eruption, at an average downcutting rate of 5 mm/yr since 3.6 Ma.

ACKNOWLEDGMENTS

REFERENCES

ALLEGRE, C.J., DUPRE, B., RICHARD, P. & ROUSSEAU, D., 1982. Sub-continental versus suboceanic mantle, II. Nd-Sr-Pb isotopic comparison of continental tholeiites with mid-ocean ridge tholeiites, and the structure of the continental lithosphere. *Earth and Planetary Science Letters* 57: 25-34.

ANDERSON, J.A.C., PRICE, R.C. & FLEMING, P.D., 1998. Structural analysis of metasedimentary enclaves: implications for tectonic evolution and granite petrogenesis in the southern Lachlan

Fold Belt, Australia. *Geology* 26 (2): 119-122.

BOLGER, P.F. & KING, R.L., 1976. *Tallangatta SJ 55-3 1: 250 000 Geological Sheet*, Geological Survey of Victoria.

BONHOMME, M.G., THUIZAT, R., PINAULT, Y., CLAUER, N., WENDLING. R. & WINKLER, R., 1975. *Methode de datation potassium-argon*. Appareillage et Technique. CNRS CGS (Centre de Geochemie de la surface) internal report, Universite Louis Pasteur, Strasbourg, 53pp.

CARLSON, R.W., 1991. Physical and chemical evidence on the cause and source characteristics of flood basalt volcanism. *Australian Journal of Earth Sciences* 38: 525-544.

CARLSON, R.W., LANGMUIR, G.W. & MACDOUGALL, J.D., 1981. Columbia River volcanism: the question of mantle heterogeneity or crustal contamination. *Geochimica et Cosmochimica Acta* 45: 2483-2499.

CAS, R., 1983. *Palaeogeographic and tectonic development of the Lachlan Fold Belt, southeastern Australia*. Geological Society of Australia, Special Publication 10, 104pp.

CHESLEY, J.T. & RUIZ, J., 1998. Crust-mantle interaction in large igneous provinces: implications from the Re-Os isotope systematics of the Columbia River flood basalts. *Earth and Planetary Science Letters* 154: 1-11.

EASTON, J.G., 1937. Gibbo River. - Alluvial Deposits. *Records of the Geological Survey of Victoria* 5(4): 507-509.

EWART, A., CHAPPELL, B.W. & MENZIES, M., 1988. An overview of the geochemical and isotopic characteristics of the Eastern Australian Cainozoic volcanic provinces. *Journal of Petrology*, Special Lithosphere Issue, Oxford University Press, Oxford, 225-273.

FAURE, G., 1986. *Principles of Isotope Geology*, John Wiley, New York, USA, 589pp.

GRAY, D.R., 1997. Tectonics of the southeastern Australian Lachlan Fold Belt: structural and thermal aspects. In *Orogeny through Time*, J-P. Burg & M. Ford, eds., Geological Society, London, Special Publication 121, 149-177.

HAWKESWORTH, C.J. & VOLLMER, R., 1979. Crustal contamination vs enriched mantle: $^{143}Nd/^{144}Nd$ and $^{87}Sr/^{86}Sr$ evidence from the Italian volcanics. *Contributions to Mineralogy and Petrology* 69: 151-165.

HEINRICHS, H. & HERRMANN, A.G., 1990. *Praktikum der Analytischen Geochemie*. Springer-Verlag, Berlin-Heidelberg, 669pp.

HILLS, E.S., 1938. The age and physiographic relationship of the Cainozoic volcanic rocks of Victoria. *Proceedings of the Royal Society of Victoria* 51: 112-139.

HOFMANN, A.W., JOCHUM, K.P., SEUFERT, M. & WHITE, W.M., 1986. Nb and Pb in oceanic basalts: new constraints on mantle evolution. *Earth and Planetary Science Letters* 79: 33-45.

HOWITT, A.W., 1879. Notes on the Physical Geography and Geology of North Gippsland. *Quarterly Journal of the Geological Society* 35 (5): 1-41.

HUANG, Y., HAWKESWORTH, C.J., VAN CALSTEREN, P., SMITH, I. & BLACK, P., 1997. Melt generation models for the Auckland volcanic field, New Zealand: constraints from U-Th isotopes. *Earth and Planetary Science Letters* 149: 67-84.

LE MAITRE, R.W., 1989. *A Classification of igneous rocks and glossary of terms*. Blackwell Scientific Publications, 193pp.

MACDONALD, G.A. & KATSURA, T., 1964. Chemical composition of Hawaiian lavas. *Journal of Petrology* 5: 82-113.

McBRIDE, J.S., LAMBERT, D.D., NICHOLLS, I.A. & PRICE, R.C., 2001. Osmium isotopic evidence for crust-mantle interaction in the genesis of continental intraplate basalts from the Newer Volcanics Province, Southeastern Australia. *Journal of Petrology* 42(6): 1197-1218.

McDONOUGH, W.F., McCULLOCH, M.T. & SUN, S.S., 1985. Isotopic and geochemical systematics in Tertiary-Recent basalts from southeastern Australia and implications for the evolution of the sub-continental lithosphere. *Geochimica et Cosmochimica Acta* 49: 2051-2067.

McDOUGALL, I., ALLSOPP, H.L. & CHAMALAUN, F.H., 1966. Isotopic dating of the Newer Volcanics of Victoria, Australia, and geomagnetic polarity epochs. *Journal of Geophysical Research* 71: 6107-6118.

McDOUGALL, I. & ROKSANDIC, Z., 1974. Total fusion $^{40}Ar/^{39}Ar$ ages using HIFAR reactor. *Journal of the Geological Society of Australia* 21: 81-89.

NICHOLLS, I.A., GREIG, A.G., GRAY, C.M. & PRICE, R.C., 1993. *Newer Volcanics Province - basalts,*

xenoliths and megacrysts. Australian Geological Survey Organisation, Canberra. IAVCEI Canberra Excursion Guide, 48 pp.

PRICE, R.C., GRAY, C.M., NICHOLLS, I.A. & DAY, A., 1988. Cainozoic volcanic rocks. In *Geology of Victoria* J.G. Douglas & J.A. Ferguson, eds., Geological Society of Australia, Victorian Division Special Publication, 439-451.

PRICE, R.C., GRAY, C.M., WILSON, R.E., FREY, F.A. & TAYLOR, S.R., 1991. The effects of weathering on rare-earth element, Y and Ba abundances in Tertiary basalts from southeastern Australia. *Chemical Geology* 93: 245-265.

PRICE, R.C., GRAY, C.M. & FREY, F.A., 1997. Strontium isotopic and trace element heterogeneity in the plains basalts of the Newer Volcanic Province, Victoria, Australia. *Geochimica et Cosmochimica Acta* 61(1): 171-192.

PRICE, R.C., NICHOLLS, I.A. & GRAY, C.M., 2003. Cainozoic igneous activity. In *Geology of Victoria* W.D. Birch, ed., Geological Society of Australia Special Publication 23. Geological Society of Australia (Victoria Division), 361-375.

STEIGER, R.H. & JAGER, E., 1977. Subcommission on Geochronology: convention on the use of decay constants in geo- and cosmo-chronology. *Earth and Planetary Science Letters* 36: 359-362.

STEWART, K. & ROGERS, N., 1996. Mantle plume and lithosphere contributions to basalts from southern Ethiopia. *Earth and Planetary Science Letters* 139: 195-211.

SUN, S-S., 1982. Chemical composition and origin of the Earth's primitive mantle. *Geochimica et Cosmochimica Acta* 46: 179-192.

SUTHERLAND, F.L., 2003. 'Boomerang' migratory intraplate Cenozoic volcanism, eastern Australian rift margins and the Indian-Pacific mantle boundary. In *Evolution and Dynamics of the Australian Plate*, R.R. Hillis, and R.D. Muller, eds., Geological Society of Australia Special Publication 22

and Geological Society of America Special paper 372, 203-221.

TAYLOR, S.R. & MCLENNAN, S.M., 1985. *The Continental Crust: its composition and evolution.* Blackwell, Oxford, 312pp.

THOMPSON, R.N., MORRISON, M.A., DICKIN, A.P. & HENDRY, G.L., 1983. Continental Flood Basalts...arachnids rule OK?. In *Continental Basalts and Mantle Xenoliths*, C.J. Hawkesworth & M.J. Norry, eds., Nantwich: Shiva, 159-185.

TURNER, S. & HAWKESWORTH, C., 1995. The nature of the sub-continental mantle: constraints from the major-element composition of continental flood basalts. *Chemical Geology* 120: 295-314.

VOGEL, D.C. & KEAYS, R.R., 1997. The petrogenesis and platinum-group element geochemistry of the Newer Volcanic Province, Victoria, Australia. *Chemical Geology* 136: 181-204.

WELLMAN, P., 1974. Potassium-argon ages on the Cainozoic volcanic rocks of eastern Victoria, Australia. *Journal of the Geological Society of Australia* 21 (4): 359-376.

WELLMAN, P. & MCDOUGALL, I., 1974. Cainozoic igneous activity in Eastern Australia. *Tectonophysics* 23: 49-65.

WILLMAN, C.E., MORAND, V.J., HENDRICKX, M.A., VANDENBERG, A.H.M., HAYDON, S.J. & CARNEY, C., 1999. Omeo 1: 100 000 map and geological report. *Report of the Geological Survey of Victoria 118*.

ZHANG, M., O'REILLY, S.Y. & CHEN, D., 1999. Location of Pacific and Indian mid-ocean ridge-type mantle in two time slices: evidence from Pb, Sr and Nd isotopes from Cenozoic Australian basalts. *Geology* 27: 39-42.

ZHANG, M., STEPHENSON, P.J., O'REILLY, S.Y., MCCULLOCH, M.T. & NORMAN, M., 2001. Petrogenesis and geodynamic implications of Late Cenozoic basalts in North Queensland, Australia: trace element and Sr-Nd-Pb isotope evidence. *Journal of Petrology* 42(4): 685-719.

ZINDLER, A. & HART, S., 1986. Chemical geodynamics. *Annual Review of Earth and Planetary Sciences* 14: 493-571.